DEVELOPMENT OF ADVANCED FAR-INFRARED PHOTOCONDUCTOR ARRAYS

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ABSTRACT

The SIRTF 32x32 Ge:Ga array is the largest format far-infrared array. It is constructed from a stack of 4x32 pixel modules, forming a filled array with no inactive area between pixels. We describe the development of a 64x64 array based on the SIRTF architecture. The array consists of 4x64 modules, each with eight 32-channel cryogenic readouts. The new readout features selectable gains, permitting operation at a variety of backgrounds including those present in airborne observatories like SIRTF. The readout also features an auto-zero circuit that compensates for input threshold variations. We have constructed a 4x64 prototype module, and this device is under test.

INTRODUCTION

Germanium photoconductors have been the detectors of choice for space astronomical observations in the far infrared. Beginning with the IRAS survey, continuing with the pointed observations of ISO a decade later, and leading to the soon-to-be launched SIRTF observatory, germanium photoconductor detectors have been used as the key long wavelength detectors for these missions. At other wavelengths, the development of detector arrays has provided revolutionary increases in the sensitivity, observing speed, and quality of observations. Due to a number of technical challenges, the development of large format arrays in the far infrared has greatly lagged the shorter wavelengths, and it has only been with SIRTF that reasonably large arrays have become available[1]. The SIRTF/MIPS 32x32 format Ge:Ga still represents the largest detector array at these wavelengths (50 – 100 μm).

Larger format arrays will be highly desirable for future missions. Despite the efforts to produce large format bolometer arrays, photoconductor arrays should continue to have application for a number of reasons. Bolometers can have longer wavelength response and higher quantum efficiency than currently available photoconductors. Photoconductors, however, have two significant advantages at the systems level. First, photoconductors can operate at much higher temperatures than bolometers. For example, the Ge:Ga detectors on SIRTF operate at 1.5 K, but to achieve comparable performance, bolometers would need temperatures near 0.1 K. The second, related advantage is that there exists a high performance silicon readout technology that functions well at the same temperature as the detectors. The system simplification made possible by these readouts is significant.

We report on the effort at the University of Arizona to produce a 64x64 germanium photoconductor array. The architecture of this array is based on the 32x32 SIRTF array. The SIRTF array is optimized for very low background space observations. Backgrounds for observations from SOFIA will be orders of magnitude higher. To accommodate use on airborne facilities, we have developed a new cryogenic readout that has been expressly designed for these high backgrounds. We report on test results for this device. Finally, we report the construction of a 4x64 prototype module incorporating these components.

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DESIGN CONSIDERATIONS

Detector Geometry

The absorption coefficient $\alpha(\lambda)$ in a photoconductor is given by the product of photoionization cross section $\sigma(\lambda)$ and doping concentration N_d. For germanium, the principal dopants that have been investigated are Be, Ga, P, and Sb. For all these elements, the photoionization cross section lies between 1 x 10^{-14} to 1.6 x 10^{-14} cm^{-2} [2]. The maximum doping in conventional photoconductors is set by the onset of impurity hopping conduction, which results in an unacceptable increase in dark current. For all these dopants, the concentration limit is ~1 x 10^{14} cm^{-2}, so the absorption coefficients are ~1-1.6 cm^{-1}. Consequently, for adequate infrared efficiency, the detector elements must have long absorption lengths. This long absorption length can be accomplished by either having physically large detectors or by trapping the photons for multiple passes through the detector. Alternatively, Blocked Impurity Band detectors promise significantly higher doping concentrations if the technical challenges can be solved[3].

The long required absorption path length led us to the detector configuration shown in Figure 1. The photoconductor consists of four long transversely illuminated bars of germanium that have been delineated into individual pixels by etching. Detector bias is applied to a common contact on the top surface of the detector, and the individual pixel signals are brought out on traces on the fanouts. The infrared radiation enters via an undoped germanium optical concentrator. The concentrator provides clearance for the fanout that supports the detector, giving a 100% fill factor. The concentrator is attached to the fanout and photoconductor with a thin, transparent epoxy joint that provides a modest amount of index matching. The thickness of the joint is maintained to less than 10µm to minimize interference effects. The reflector bar is a metallized sapphire bar placed in close proximity to the photoconductor. It reflects infrared radiation back into the photoconductor to give a second pass through the detector.

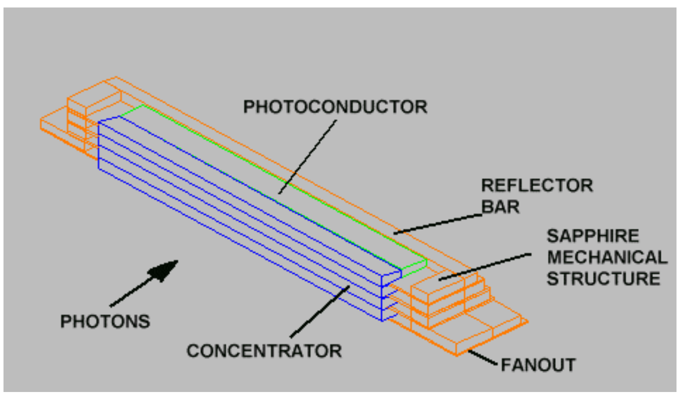

Figure 1. Detector Assembly

The need for isolation of the detector from the readout also points to this indirect hybrid approach. Although we have developed a readout that operates at the same temperature as the detectors, the readouts still dissipate a modest amount of heat (~1 µW per pixel). Mounting the readout and the detector on separate substrates minimizes potential thermal interactions. More significant is the need for optical isolation between the readout and the detector. A well known problem with silicon readouts is the amplifier "glow", a non-thermal emission from circuits in the readout. The indirect hybrid approach naturally isolates the readout from the detector, minimizing this extraneous background.

Readout Considerations

Germanium photoconductors operate at relatively low bias voltages. Ge:Ga, for example, has a typical bias of ~50 mV for a 0.5 mm thick detector. This low bias places special constraints on the readout. Linearity and uniformity of operation require that the bias on a detector not change significantly during an observation. Additionally, the detectors are consequently particularly sensitive to small amplifier instabilities in the operating point. A significant effort in readout development has led to solution in both the DC stability and bias maintenance requirements.

Conventional silicon CMOS circuits exhibit a wide variety of undesirable characteristics at low temperatures. These behaviors include carrier freezeout, unstable DC response, hysteresis, and non-linear response function[4]. Most of these characteristics show up below 20 K. A key part of the SIRTF development effort was the production of high performance cryogenic readouts that avoided all of these anomalies. The critical processing enhancements needed to make a true cryogenic readout are:

1) Degenerately doped substrate,
2) Thin, lightly doped epitaxial layer, and
3) Highly doped contacts.

The SIRTF readouts, the CRC-696 produced at Raytheon Newport Beach, proved to have excellent stability even at sub-Kelvin temperatures. Since both p- and n-channel devices are present with good performance, the full suite of circuit possibilities could be exploited in readout design. In particular, the ability to incorporate CMOS logic and high gain inverting amplifiers proved to be useful.

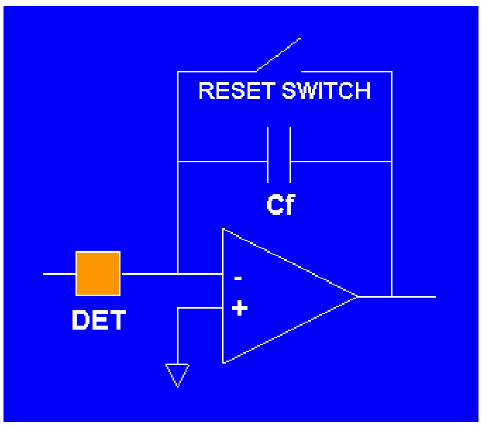

Figure 2. CTIA Block Diagram

The choice of unit cell requires special consideration. Because of the very low biases on the detector, a conventional source follower circuit where the charge is integrated on the input capacitance is of limited use. The change in voltage at the input node is given by $\Delta V = \Delta Q\ C_{in}$, where ΔQ is the accumulated charge and C_{in} is the imput capacitance. For linear operation, ΔV should be a small fraction of the applied bias. Hence, the conventional source follower has a very limited full well capacity for germanium detectors.

An alternative circuit is the capacitive transimpedance amplifier, shown in block form in Figure 2. With this circuit, the integrating capacitance is no longer the input capacitance, but rather a capacitor put in the feedback loop of an inverting differential amplifier. The negative feedback maintains the input node at a very constant potential, and the allowed voltage swing on the capacitor is now set by the amplifier swing rather than the few millivolts of allowed detector debiasing. The output signal is given by $\Delta V = \Delta Q\ C_f$, where C_f is the feedback capacitor. For the SIRTF readouts, C_f is 36 fF, giving a large transconductance of 4 µV/electron. An additional characteristic of the CTIA is beneficial. Because the electrical potential at the detector and the external interconnects is constant due to the negative feedback, there is no electrical crosstalk in this circuit.

MOTIVATION FOR A SOFIA LARGE FORMAT ARRAY

SOFIA will nicely complement the capabilities of SIRTF. As a cryogenic space telescope, SIRTF will be very much more sensitive than SOFIA; as a larger telescope, however, SOFIA will have significantly better angular resolution. SOFIA will, of course, also be able to benefit from new generations of detectors and instrumentation. Prime examples of additional classes of observation include polarimetry and narrow-band imaging in emission lines.

Groundbased array cameras have shown that the fixed relation of one pixel to another (as compared to images made by mosaicing observations with single detectors or small arrays) and the ability to oversample the PSF while still providing a reasonable field of view provide large gains in the accuracy of imaging observations.

A 64x64 detector array is a scale that will be very useful for exploiting the capabilities of the SOFIA telescope. A $\lambda/2D$ pixel at 70 µm would be 2.9", and a 64x64 array would subtend 3'. This size array would allow the modulation of small extended objects such as galaxies on the array. A 3' field of view also makes the mapping of many extended objects practical. Figure 3 shows an ISOCAM 15 µm image of Centaurus A compared to the field of view of a 64x64 detector array. Also shown is the field of view of the First-light instrument HAWC.

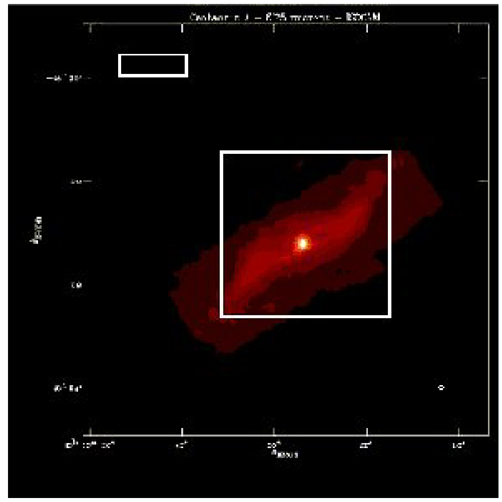

Figure 3. ISOCAM 15 µm Image of Centaurus A and the field of view of a 64x64 array at 70 µm.

SBRC-190 DEVELOPMENT

The CRC-696 design was optimized for the low backgrounds of SIRTF, but the background flux will be more than 10^6 higher on SOFIA. To accommodate these high backgrounds, we undertook a joint development in collaboration with Ed Erickson to make a new readout better suited to airborne applications. The new device, the SBRC-190, is based on the CRC-696, but it has a number of important enhancements for the new application. First, the SBRC-190 has eight selectable gain stages with widely varying full well capacities. Table 1 gives the different feedback capacitances. Second, the SBRC-190 incorporates an auto-zero circuit at the input stage. The detector signal is capacitively coupled to the input via a large capacitor. The DC bias point is set by a switch that momentarily connects the input node to a defined bias. Third, the SBRC-190 includes a built-in sample and hold circuit. The S/H simplifies the synchronization of the data stream by allowing simultaneous sampling of all channels in the readout prior to multiplexing. This synchronization is important in airborne applications where a chopping secondary mirror may be used. Figure 4 shows the schematic of the SBRC 190 unit cell. This unit cell is replicated for each of the 32-channels.

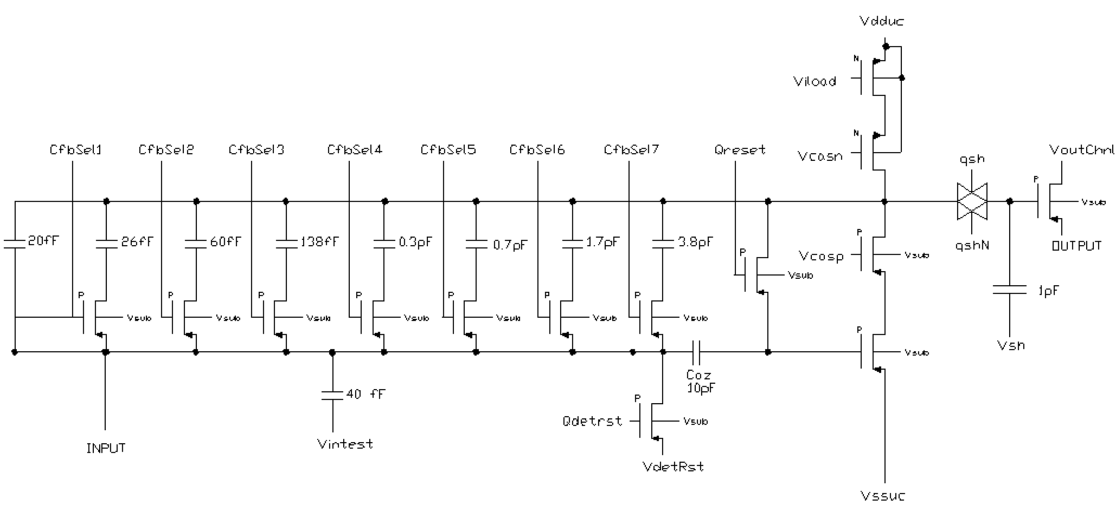

Figure 4. SBRC-190 Schematic

Table 1. SBRC Gains

Gain Name	Cf (fF)	Full Well (e)	Read Noise (e)
Cfb0	20	1.7×10^5	250
Cfb1	46	3.8×10^5	270
Cfb2	106	8.8×10^5	300
Cfb3	243	2.0×10^6	330
Cfb4	560	4.7×10^6	300
Cfb5	1300	1.1×10^7	400
Cfb6	2900	2.4×10^7	700
Cfb7	6800	5.7×10^7	1500

A number of lots of the SBRC-190 were produced at the Raytheon Newport Beach facility prior to its shutdown. The produced lots have generally not met the parametric specifications in terms of p-channel threshold uniformity. In the case of the CRC-696, these variations would have resulted in unacceptable variations in the detector bias. However, the auto-zero circuit of the SBRC-190 to a large extent compensates for these variations, and the existing devices are quite usable. Initial testing of these devices has been reported by Farhoomand et al.[5] at this workshop. Performance of the SBRC-190 has been verified in our laboratories at temperatures as low as 2 K. Currently, there is no demonstrated alternative to the Newport Beach capability. We have enough readouts for the 64x64 array development, but future photoconductor arrays will require a new readout effort.

MODULE DESIGN

The basic architecture of the 4x64 module is very similar to the 4x32 design of the SIRTF array. Small adjustments in the pixel dimensions have been made to improve yields, most notably, an increase in pixel pitch from 750 µm to 800 µm. The increased thickness of the layers goes into an increase in the fanout thickness (from 125 µm to 175 µm), resulting in a substantial increase in strength.

A new Ceramic Multilayer Board Design has been fabricated. This CMLB accommodates eight SBRC-190 readouts, and has eight balanced outputs. Unlike the SIRTF focal plane array, each output has an active reference line that is fed by an unconnected 33rd channel of the readout. This reference line, to first order, corrects for any drifts in the SBRC-190 outputs. Figure 5 shows the CMLB design.

As is done with the SIRTF array, the CMLB is mounted in a molybdenum frame. Molybdenum is chosen for its combination of high thermal conductivity and its excellent thermal expansion match to the alumina

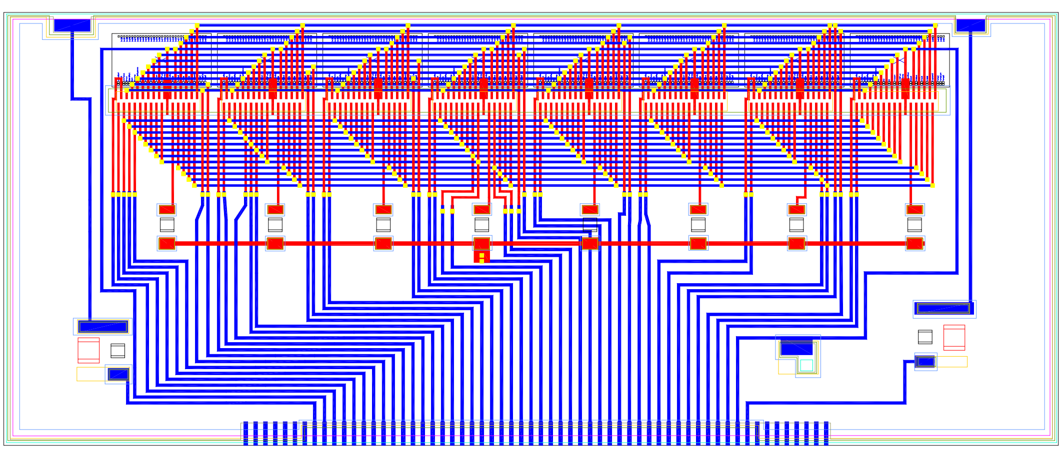

Figure 5. 4x64 Module Ceramic Multilayer Board

CMLB and the sapphire detector bars. The pixels are wire bonded to the readout inputs. The wire bonding process requires special procedures since the detector pads on the fanouts lie on four different layers. The wire bond pattern interleaves the signals from these layers. When interleaved, the pixel pitch of 800 μm is a good match to the resulting pitch of the readout bond pads (4 x 175 μm = 700 μm).

Figure 6 is a photograph of an assembled 4x64 module. The unit is undergoing initial testing at the University of Arizona.

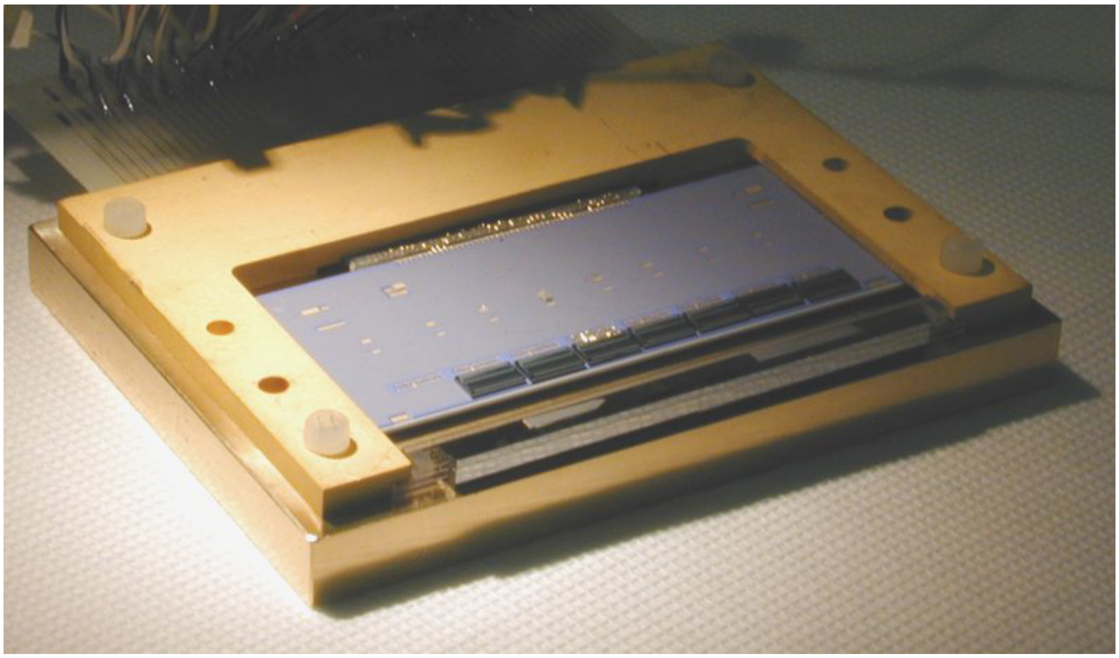

Figure 6. 4x64 Ge:Ga Detector Module

SUMMARY

Based on the flight-qualified SIRTF design for the 32x32 Ge:Ga far infrared array, we have begun the development of a 64x64 array suitable for a SOFIA imager. A key part of this effort has been the production of a cryogenic CTIA readout that has much higher well capacities than the CRC-696. This device also has additional circuit enhancements that correct for input threshold non-uniformities and allow for simultaneous sampling of the 32 channels. We have constructed a 4x64 module that incorporates a detector bar, CMLB, molybdenum frame, readouts, and output cable.

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